PHOTOGRAPHIC OBSERVATIONS OF *ALGOL*.

By Sidney D. Townley.

During the fall of 1892, while at the Lick Observatory, I made a series of observations to test the value of photographic methods for the determination of the changes in variable stars. After experimenting for a couple of months with various lenses, I obtained the use of the Crocker photographic telescope, which has a Willard lens of 5.9 inches aperture and 30.7 inches focal length. This is one of the instruments employed by Professor Schaeberle in the determination of his formulæ for photographic magnitudes and atmospheric absorption of photographic rays, published in *Contributions from the Lick Observatory*, No. 3.

The size of an image of a star on a photographic plate, for any particular telescope and any particular plate, will be a function of the time of exposure and the brightness (photographic) of the star. Conversely, the size of the image of any particular star, for any given time of exposure, will depend upon the constants of the instrument, such as aperture, focal length, etc., and the "quickness" of the photographic plate.

It is then possible to determine, from experiments, for any particular telescope and plate, an empirical formula which shall express the photographic brightness of a star as a function of the time of exposure and diameter of the image. Professor Schaeberle has made such an investigation as this, and published, in the contribution named above, a table in which the brightness or photographic magnitude is given as a function of the arguments, time of exposure, and the measured diameter of the image.

As a starting point for magnitudes, Professor Schaeberle assumed the photographic magnitude of *Polaris*, at its mean zenith distance at Mount Hamilton, to be 2.00. This was merely provisional, however, for at that time the effect of atmospheric absorption was not known. By his investigation of this subject, Professor Schaeberle found the atmospheric absorption of the photographic rays of *Polaris*, at its mean zenith distance at Mount Hamilton, to be 0.51 of a magnitude. This has been applied as a correction to the functions of the table, so that the

standard now assumed is, that *Polaris*, at a zenith distance of zero, shall have a photographic magnitude of 2.00.

Inasmuch as I used the same telescope and the same kind of plate, Seed 26, as were employed by Professor SHAEBERLE, the formulæ derived by him should be directly applicable to my work. In every respect I endeavored to follow Professor SCHAEBERLE'S methods in order to make the personal differences as small as possible.

The program of work consisted of making three exposures of two, four and eight seconds, which was later changed to four, eight and sixteen seconds, every ten or twenty minutes, for a period of several hours on each side of the computed time of minimum. All the exposures of one night were made upon the same plate, and kept as near as possible to the center. Several exposures of *Polaris*, of four, eight and sixteen seconds, were also made upon each plate, usually both at the beginning and the end of each night's work.

At first I used the measuring engine of the LICK Observatory for measuring the images; but this was unsatisfactory, for even with the lowest magnifying power the images were large and not sharply defined, so that it was impossible to make accurate measurements. I afterwards constructed a scale upon mica by drawing two very fine lines at a small angle to each other, and then making several similar triangles by drawing cross-lines perpendicular to the line bisecting the angle. The bases of the triangles were so placed that each differed from the preceding by $\frac{1}{1000}$ of an inch; so that, with a small magnifying power, it was possible to read off the diameter of an image to $\frac{1}{10000}$ of an inch. I always measured two diameters at right angles to each other. The results show that in general the images are round. All the measurements were made by lamplight, which was always, as nearly as possible, of the same intensity. All the measurements of any plate were made at one sitting, in order to avoid systematic differences which might otherwise enter.

The measured diameters of *Polaris* d_m generally differed slightly from the tabulated values d_t, and the correction, $\Delta d = d_t - d_m$, was determined for each plate and applied as a correction to each measured diameter of the variable, d_v. The resulting magnitudes of the variable were corrected for atmospheric absorption by means of the table upon page 86 of the work above mentioned. The time of minimum was then de-

termined by plotting these corrected magnitudes and drawing a smooth curve through them.

Upon several nights, while photographing *Algol*, I also made visual observations. The comparison stars used were α *Persei* $1^m.9$, γ *Andromedæ* $2^m.1$, β *Triangulæ* $3^m.2$, and δ *Persei* $3^m.3$. The magnitudes correspond to SCHÖNFELD's standard light scale, with the exception of α *Persei*, which was not used by him. ρ *Persei* was also used upon the first night, but as it is variable it was not employed upon subsequent occasions. The magnitude of ρ *Persei* was assumed to be 3.1. While making the visual observations, and also while measuring the plates, I took particular pains not to know the exact computed time of minimum.

The following table gives the minima determined. The time used is Pacific Standard time, 8 hours slow of Greenwich. The computed times of minimum are from CHANDLER's table, *Astronomical Journal*, Vol. VII, No. 167. The result of October 31 is given but half weight, as the zenith distance was very large at the time of minimum.

MINIMA OF *ALGOL*.

Photographic.			Visual.	$O_p - C.$	$O_v - C.$	$O_p - O_v$
		D. H. M.	H. M.	M.	M.	M.
1892.	Oct.	25 14 2.2	. . .	+47.8	. . .	. . .
		28 10 39.6	. . .	+35.4	. . .	. . .
		31 8 2.7	. . .	+69.6	. . .	. . .
	Nov.	20 9 52.6	8 57.0	+77.5	+21.9	+55.6
	Dec.	7 14 25.5	14 3.0	+57.3	+35.8	+21.5
		10 11 0.5	10 33.9	+43.4	+16.8	+26.6
1893.	Jan.	2 8 48.1	9 4.6	+ 0.2	+16.7	−16.5
MEAN				+45.6	+22.8	+21.8

In most cases there is considerably more difference than one would expect between the observed photographic and visual minima. It is not likely that this difference is real, and as in every case except one, the visual minimum is nearer the computed, the inference is strong that the photographic method is affected by some uneliminated systematic errors. There is a large and consistent deviation of the visual minima from the computed ones, of which, however, I see no explanation.

In the following table I give in detail the observations of 1893,

January 2, in order to show what degree of accuracy has been obtained in the photographic method. I have chosen this date because at the beginning of the series I was inexperienced in photographic work, so that observations taken in the latter part may fairly be presumed to be more free from errors of inexperience and thus to better represent the true worth of the method. A mean solar chronometer set to Pacific Standard time was used in making the exposures. The chronometer correction was $-6^m\ 22^s$. The times given in column one are readings of the chronometer face. It took about a minute each time to make the exposures of four, eight and sixteen seconds. The beginning and the end of the operation were recorded and the time given is the mean of these two. The visual observations were made immediately after the exposures, so that a correction of about a minute should be applied to each of the recorded times of observation. This correction has been applied in deriving the visual minima. A second set of measurements of the images was made, with the same scale, more than a year after the first set. Both are given in the table for comparison. While making the second set of measurements, I had entirely forgotten the results obtained in the first set and took particular pains not to look at the first set until after the second was finished. For the first set $\Delta d = -0.0011$ inches and for the second -0.0006. In some cases the differences are rather large and this shows that there is considerable uncertainty in such measurements. The resulting time of minimum, however, is changed only a few minutes.

Time.	4^s Exposure.		8^s Exposure.		16^s Exposure.		Corrected Mean.		Difference	Visual Observation.	Visual Mag.
	1st Set.	2d Set.	1st Set.	2d Set.	1st Set.	2d Set.	1st Set.	2d Set.			
H. M.	M.	M.	M.	M.	M.	M.	M.	M.	M.		
6 50.5	1.74	1.84	1.57	1.79	1.73	1.67	2.14	2.23	−0.09	$a6\delta$, $c5b$	2.70
7 0.5	1.74	1.84	1.69	1.74	1.73	1.69	2.19	2.23	−0.04		
10.5	1.81	1.91	1.74	1.81	1.75	1.71	2.25	2.29	−0.04		
20.5	1.78	1.91	1.81	1.92	1.84	1.73	2.30	2.34	−0.04	$a7\delta$, $c6b$	2.82
40.5	1.88	1.94	1.92	1.95	1.90	1.84	2.40	2.41	−0.01	$a8\delta$, $c8b$	3.00
8 0.5	1.95	2.01	2.07	2.02	1.98	1.90	2.50	2.48	+0.02	$a9\delta$, $c9b$	3.12
10.5	2.18	2.15	2.15	2.05	2.05	1.98	2.64	2.57	+0.07		
20.5	2.35	2.18	2.20	2.05	2.11	2.06	2.73	2.61	+0.12	$\beta\delta$, βb	3.25
30.5	2.65	2.35	2.33	2.12	2.23	2.11	2.91	2.70	+0.21		
40.5	2.94	2.45	2.62	2.17	2.36	2.19	3.15	2.78	+0.37	$\delta 1\beta$, βb	3.30
9 0.5	2.77	2.56	2.40	2.40	2.25	2.26	2.97	2.91	+0.06	$\delta 1\beta$, $b1\beta$	3.35
10.5	2.81	2.48	2.40	2.37	2.23	2.19	2.98	2.85	+0.13		
20.5	2.73	2.56	2.35	2.35	2.23	2.17	2.93	2.85	+0.08	$\delta 2\beta$, $b1\beta$	3.40
30.5	2.52	2.45	2.25	2.30	2.11	2.15	2.77	2.78	−0.01		
40.5	2.38	2.35	2.22	2.20	2.13	2.09	2.71	2.68	+0.03	$\delta 1\beta$, $b\beta$	3.30
50.5	2.35	2.28	2.15	2.12	2.05	2.02	2.65	2.61	+0.04		
10 0.5	2.28	2.25	2.07	1.97	1.96	2.02	2.56	2.54	+0.12	$\delta\beta$, $b\beta$	3.25
10.5	2.18	2.21	1.97	1.89	1.92	1.94	2.46	2.45	+0.01		
20.5	1.98	2.04	1.89	1.84	1.86	1.92	2.34	2.36	−0.02	$a9\delta$, $c8b$	3.07
30.5	1.91	1.91	1.81	1.81	1.77	1.86	2.24	2.27	−0.03		
50.5	1.74	1.81	1.74	1.76	1.73	1.80	2.11	2.16	−0.05	$a8\delta$, $c7b$	2.95
11 10.5	1.64	1.74	1.72	1.74	1.65	1.67	2.00	2.05	−0.05		
20.5	1.56	1.78	1.67	1.66	1.59	1.61	1.92	1.99	−0.07	$a8\delta$, $c7b$	2.95
40.5	1.58	1.74	1.61	1.66	1.58	1.61	1.86	1.94	−0.08	$a7\delta$, $c6b$	2.82
12 0.5	1.54	1.74	1.59	1.71	1.55	1.58	1.77	1.89	−0.12		
20.5	1.52	1.64	1.55	1.66	1.52	1.52	1.68	1.76	−0.08	$a6\delta$, $c5b$	2.70
50.5	1.44	1.61	1.51	1.59	1.47	1.47	1.51	1.60	−0.09	$a4\delta$, $c3b$	2.45
13 0.5	1.42	1.64	1.49	1.57	1.44	1.47	1.44	1.55	−0.11		

DISCUSSION OF RESULTS.

From the measured diameters of *Polaris*, there appears a systematic difference between Professor SCHAEBERLE'S results and mine. This may arise from three causes: (*a*) Different development of plates; (*b*) Differences in the scales used; (*c*) Personal differences in the measurement of an image. The differences are probably largely due to the first cause. Following is a tabulation of the differences where $\Delta d = d_t - d_m$ as before stated:

	2^s Exposure.	4^s Exposure.	8^s Exposure.	16^s Exposure.
	IN.	IN.	IN.	IN.
Δd	$-$ 0.0002	$-$ 0.0006	$-$ 0.0007	$-$ 0.0007
r	$\pm$ 0.00017	$\pm$ 0.00028	$\pm$ 0.00026	$\pm$ 0.00029
i_0	$\pm$ 0.00003	$\pm$ 0.00003	$\pm$ 0.00003	$\pm$ 0.00004
n	24	63	64	45

There are also differences in the magnitudes determined from different exposure times. Each determination of the magnitude of the variable is the mean of three practically simultaneous exposures of different lengths. Theoretically, of course, the three exposures should all give the same magnitude. The following table will show the differences:

	Mag.	n.
$2^s - 4^s$	$-$ 0.03	74
$4^s - 8^s$	+ 0.08	319
$8^s - 16^s$	+ 0.08	217

Here the probable errors are large and an inspection of the individual observations, especially the results of those plates which were measured twice, shows that the differences depend largely upon circumstances of measurement, so that the apparent systematic differences may be accidental. A photographic image is never perfectly definite in outline, so that the measurement of its diameter involves the judgment to a certain extent, and therefore the same images measured under different circumstances may yield quite different results.

Observations on a number of dates, when the star reached a considerable zenith distance, seem to show that the formula derived by Professor SCHAEBERLE for atmospheric absorption of photographic rays, gives corrections which are too large. In

1893, January 6, I made a series of observations to test the formula and found my suspicions strengthened. Upon that date *Algol*, which was not going through a minimum phase, was photographed every ten or twenty minutes from a zenith distance of 6° to 78°.8. The resulting magnitudes corrected by the formula for absorption should all be the same, but the following table shows considerable differences which increase with the zenith distance. In the first column is the zenith distance. In the second column is the resulting photographic magnitude of *Algol* corrected for absorption by the formula. The third column is the same as the second from an entirely independent measurement of the images. The fifth column gives the deviation from the formula on an assumption that the deviation at a zenith distance of 6° is insensible.

Z	Mag.	Mag.	Mean.	Error.
6	1.52	1.63	1.58	0.00
8	1.52	1.63	1.58	0.00
11	1.50	1.62	1.56	0.02
15	1.50	1.61	1.56	0.02
18	1.49	1.58	1.54	0.04
22	1.49	1.52	1.50	0.08
26	1.43	1.55	1.49	0.09
30	1.41	1.49	1.45	0.13
33	1.38	1.48	1.43	0.15
37	1.35	1.45	1.40	0.18
41	1.29	1.40	1.34	0.24
45	1.24	1.36	1.30	0.28
48.6	1.23	1.34	1.28	0.30
52.2	1.15	1.28	1.22	0.36
54.0	1.12	1.26	1.19	0.39
55.7	1.11	1.27	1.19	0.39
57.5	1.09	1.26	1.18	0.40
59.3	1.05	1.23	1.14	0.44
61.0	1.03	1.20	1.12	0.46
62.7	1.01	1.17	1.09	0.49
66.1	0.90	1.05	0.98	0.60
67.9	0.87	1.00	0.94	0.64
70.0	0.84	0.94	0.89	0.69
72.4	0.82	0.89	0.86	0.72
74.1	0.80	0.89	0.84	0.74
75.6	0.84	0.94	0.89	0.69
77.2	0.96	0.95	0.96	0.62
78.8	0.94	0.87	0.90	0.68

I intended to make some further tests of this formula, but my work was suddenly brought to a close at this point. The evidence, of course, is entirely too limited to condemn the formula, and I offer it as a suspicion. The differences are perhaps personal.

CONCLUSIONS.

If the above results can be taken as a fair sample of what may be expected in the photographic determination of variable star minima, then it is by no means certain that the new method is superior to the old one of visual observations. In the latter there are but two sources of error—that arising in estimating the differences between the variable and the comparison stars and that arising in the determination of the light scale of the comparison stars.

These particular sources of error do not occur in photographic observations, but others of perhaps as serious or more serious nature do enter. They may be enumerated briefly as follows:

First.—The magnitude is a function of the time of exposure. As the exposures are usually made by removing and replacing a cap at the objective end of the telescope there is always some uncertainty as to the time, even when the observer has a time-piece to beat seconds. This, however, need not be looked upon as a serious source of error.

Second.—It is very necessary to have a perfectly clear sky, as the presence of the least haze or clouds will vitiate the results more than in visual observations.

Third.—A perfectly uniform development of the plates, not an easy thing to get, is necessary to complete uniformity of results.

Fourth.—Perhaps one of the most serious difficulties is the lack of uniformity in the sensitiveness of the photographic film. I have found that with the best plates, and even at the distance of only one or two inches from the center, there are sometimes annoying changes of sensitiveness, which may introduce large discrepancies in the resulting magnitudes. Plates which may be very good for ordinary purposes may be entirely worthless for such work as this, for when a change of one ten-thousandth of an inch in the diameter of an image may make a change of one-tenth of a magnitude, it is easy to see that very slight changes of sensitiveness may cause large discrepancies in the results.

Fifth.—The images are always indefinite in outline, and the measured diameters are therefore dependent upon the judgment of the observer. By care and continued practice, however, the

mode of measurement may be brought to a system, and thus all but systematic errors eliminated.

Sixth.—The formulæ for determining the magnitude and for giving the atmospheric absorption are entirely empirical. Those determined for any one telescope may be worthless for another telescope, or for the same telescope with a different plate, or even perhaps for the same telescope and plate, but a different observer. Personal differences enter so largely into the formulæ that I am inclined to the belief that they can be used with entire confidence only by the person by whom they were determined

Some of these sources of error can be controlled by the use of extreme care, and the photographing of *Polaris* upon each plate helps to eliminate some of them.

In setting forth the above sources of error it has not been my purpose to condemn or to disparage the photographic method, but merely to point out some of the difficulties encountered. I am thoroughly convinced, however, that in order to obtain perfectly reliable results it is necessary to make the work entirely homogeneous, not only to the extent of always using the same telescope and plates, but to the extent that each observer must determine for *himself* formulæ for photographic magnitudes and atmospheric absorption. If this be done, and if a more perfectly sensitive film can be manufactured, then I believe that more reliable observations of the changes of short-period variable stars could be obtained than by the visual methods.

Dr. CHARLIER, of Stockholm, has published a small pamphlet, giving his photographic observations of a minimum of *Algol* in 1891, November 2. His results are more accordant than mine, and his photographic and visual minima are in a very close agreement. He finds a photographic minimum of 2.74 magnitude and a visual one of 3.4 magnitude, with a range of but 0.7 of a magnitude between the maximum and minimum photographic brightness. My observations give an average photographic minimum of 2.45 magnitude, and an average visual minimum of 3.33 magnitude. The photographic range, however, exceeds one magnitude.

Dr. CHARLIER expresses entire confidence in the photographic method, and thinks that under proper atmospheric conditions much better results can be obtained by the photographic than by the visual method.

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